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Instrumentation and Techniques. A Self-Contained, Regulated, Burst-Firing Constant-Current AC Shock Generator

(U.S.) Health Effects Research Lab, Research Triangle Park, NC

26 Oct 76

TECHNICAL REPORT DATA (Please read Instructions on the reverse before complet[e])		
1. REPORT NO. EPA-600/J-77-170	2. JOURNAL ARTICLE	3. PB80-129935
4. TITLE AND SUBTITLE INSTRUMENTATION & TECHNIQUES: A self-contained, regulated, burst-firing constant-current ac shock generator		5. REPORT DATE
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Joseph S. Ali and Lawrence Reiter		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Experimental Biology Division Health Effects Research Laboratory U.S. Environmental Protection Agency Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO. 1FA628
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Health Effects Research Laboratory RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE EPA 600/11

15. SUPPLEMENTARY NOTES

Published in: Behav. Res. Meth. & Instru. 9(4):326-333, 1977

16. ABSTRACT

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17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Instruments Shock Generator		06C

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	11
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE A02-A01

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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EPA-600/J-77-170
JOURNAL ARTICLE

Behavior Research Methods & Instrumentation
1977, Vol. 9 (4), 326-333

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A line- and load-regulated constant-current ac shock generator has been designed for animal behavior experiments. The self-contained unit has four operating modes, amplitude adjustment, and a leakage current detection circuit. A unique feature of this generator is that the good load regulation achieved by using a high-voltage source is preserved without such problems as arcing and high current density effects. Circuit schematics, along with a discussion of selected circuits, are included. Experimental data are presented to demonstrate the utility of the device.

The purpose of this paper is to describe a shock generator that produces a burst of 60-Hz ac current of carefully controlled burst width, period, and amplitude. Operation is over a burst width range from 8 msec to 16 sec and a period range of 17 msec to 36 sec. Modes of operation include automatic, manual, and modes that facilitate control by external instrumentation.

A test animal moving on an electrified grid floor presents a varying resistive load to any device used as a shock generator. Masterson and Campbell (1972) and Reus, Houser, and Paré (1971) have noted that the use of a high-voltage ac source in series with a large resistance is the most straightforward method of insuring a constant ac current through a varying load resistance. This technique, however, suffers from a serious drawback in that high current densities and even small electrical arcs can develop under certain conditions as the feet of the subject break contact with the grid. When arcs or high current densities are present, the response of the subject becomes less predictable. Designers have accommodated this problem by using lower source voltages (typically 500 V ac) and accepting the accompanying reduction in regulation with load resistance changes. However, the benefits of a high source voltage can be preserved while also preventing arcs when the animal momentarily jumps off the grid floor. The output voltage is simply voltage limited with a back-to-back Zener diode configuration. The limiting voltage is chosen at a level that supports the maximum current for which the generator is designed whenever the load resistance (animal) is at the expected upper limit. The diodes limit the output voltage and shunt the output current whenever the subject resistance exceeds this upper limit. Table 1 compares the improved load regulation that results from the use of a high-voltage source with Zener diode limiting to the more typical 500-V ac source with no limiting. The comparison is shown at four current levels, chosen to include the limits of the unit's operating range. The average subject resistance (assumed to be a rat) is shown in column 2 for each current level. This resistance was calculated using the approximate formula (Equation 1) reported in Masterson and Campbell (1972):

$$R_{av}\ (\text{kohms}) = 15.4/I\ (\text{mA}) + 11.3 \qquad (1)$$

Load regulation is shown in Table 1 in columns 3 and 4 for a 500-V ac and a 2,400-V ac source, respectively. Load regulation is here defined as the percent change in current through the load resistance due to a +300%

Table 1
Load Regulation for a +300% Resistive Load Change for Two Commonly Used Shocker Source Voltages

		Source Voltage V ac	
		500	2400
		Current Change (Percent)	
Current (mA)	R_{av} (kohms)	Calculated	Measured
2.0	19	−18.5	−6.5
1.0	26.7	−13.8	−5.0
.5	42.1	−11.2	−4.0
.1	165	− 9.0	−2.0

This report has been reviewed by the Office of Research and Development, EPA, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use. The authors wish to thank Mr. E. B. Bailey of Northrop Services Corporation for his capable assistance in construction of the ac shocker and Ms. Miriam Ash for performing the passive avoidance experiment.

increase in the load resistance from the average value given in column 2.

Other benefits accrue from the use of this technique. A common problem in shock generators is insuring that the current is delivered to the animal and not bypassed by leakage paths. A detection circuit can be driven from the voltage developed across the back-to-back Zener diodes that will indicate the presence of a leakage path before the animal is placed on the grid. The diodes on the output also greatly reduce shock hazard, since voltage is limited to 200 V rms and current is limited to 2.0 mA.

DESCRIPTION

The shock generator (see Figure 1) is designed to operate in four modes: automatic, remote, external control, and manual. In the automatic mode, the instrument generates a recurring shock burst. Both the width and the period of the shock burst can be selected on the burst width controls and the period controls, respectively (see Figure 2). Shock burst width is variable from 8.3 msec to 16 sec in two ranges; the shock period is variable from 16.7 msec to 36 sec in two ranges. Because of independent burst width and period generators, the shocker can operate at close to 100% duty cycle.

In the remote control mode, a control signal is required at the remote control input to activate the internal pulse generator. When this signal is applied, the shocker produces a shock burst, with period and width determined by the period and burst width controls, for as long as the control signal is applied to the remote control input. In the external mode of operation, a control signal is required at the external input. In this mode, the external input signal completely controls the shock burst width and period and the internal pulse generator is bypassed. The shock burst essentially tracks the external control signal with a width and period nearly the same as the signal applied to the external input. In the manual mode, one shock burst is generated each time the manual button is pressed. The width of the generated burst is selected on the burst width control.

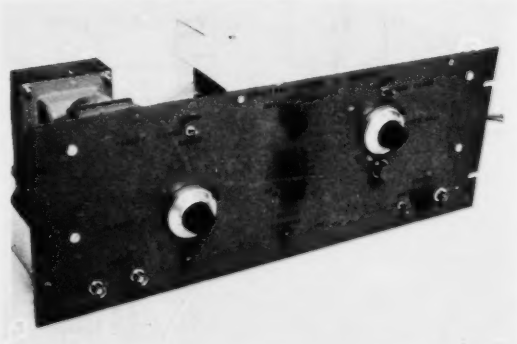

Figure 1. Constant-current ac shock generator.

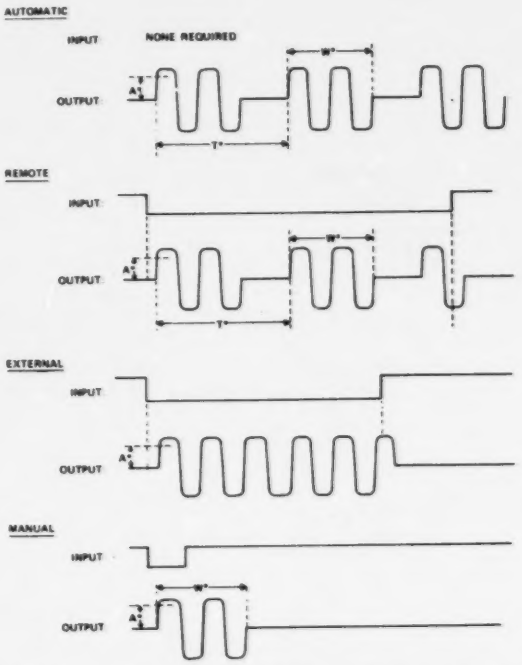

Figure 2. Shock generator output waveform for the four operating modes: A = rms current amplitude, W = burst width, T = burst period.

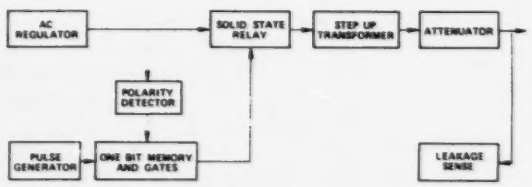

Figure 3. Block diagram of the shock generator.

Shock intensity can be varied by a rotary switch in .1-mA rms increments from .1 to 2.0 mA. Three values had to be omitted from this series (1.1, 1.4, and 1.9 mA) due to the number of positions available on the high-voltage switch used.

Two indicator lamps monitor operation of the shock generator. A red SHOCK PULSE lamp is illuminated whenever a shock pulse is generated. The green SHOCK CURRENT indicator lamp reflects the presence of current leakage paths in the grid floor shocking apparatus, which are usually caused by feces lying across the grid floor. This lamp is useful only when the animal is not on the grid. Typically, the procedure to test for leakage is simply to manually activate the generator with no animal on the grid and watch for the illumination of the SHOCK CURRENT

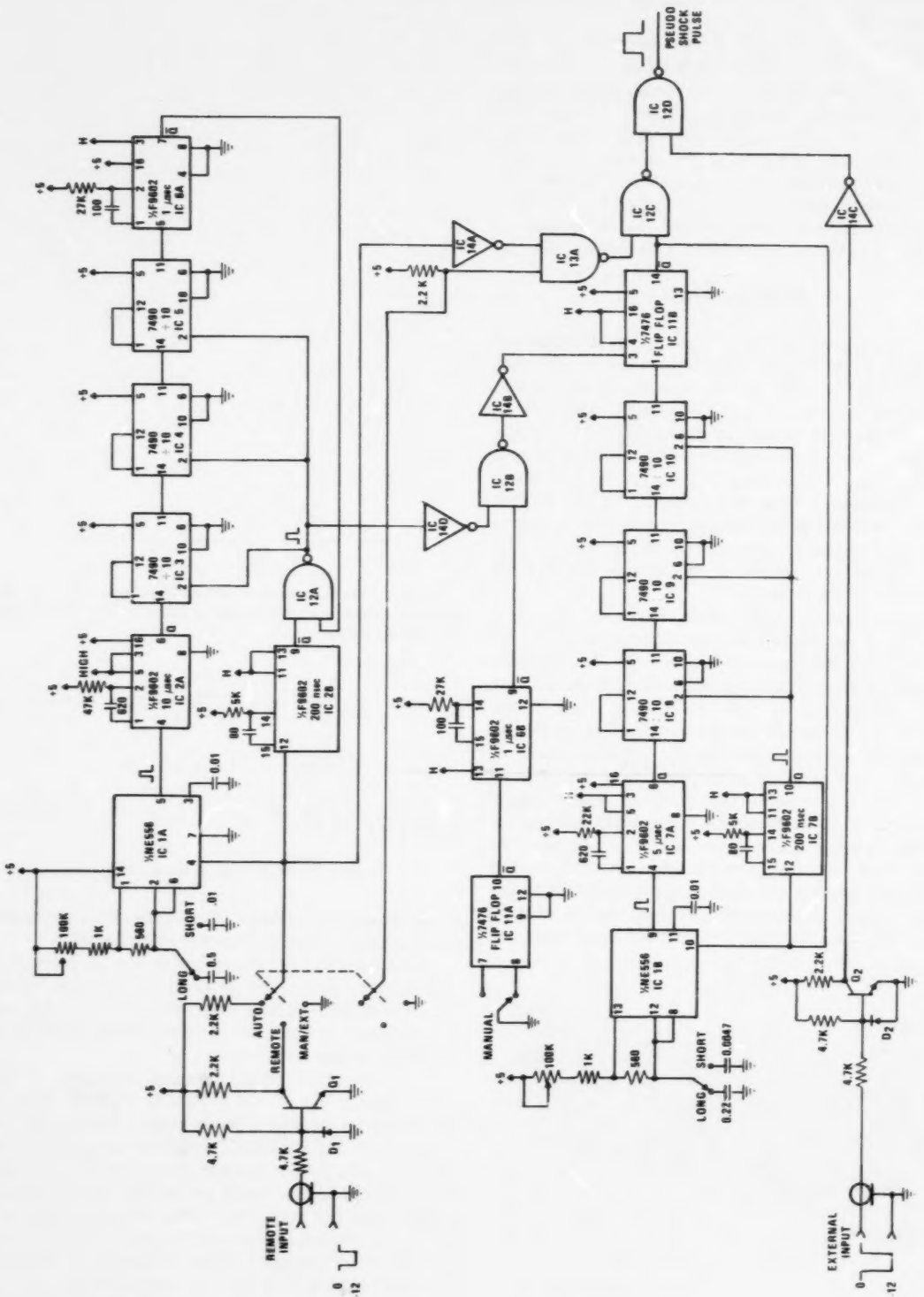

Figure 4. Schematic diagram of the pulse generator section of the shocker.

light. The green light indicates little or no leakage and, therefore, the experiment can proceed.

PRINCIPLES OF OPERATION

General

A block diagram of the shock generator is shown in Figure 3. The pulse generator (Figure 4) uses standard TTL circuitry, with the exception of the Signetics NE 556 timer. The output of the pulse generator is fed to the 1-bit memory section, where the pulse is gated through to the solid state relay at the appropriate time. The 1-bit memory stores the last polarity of the 60-Hz waveform from the previous shock pulse. The polarity detector and 1-bit memory circuits are essential to proper instrument operation because the step-up transformer remains magnetized (prebiased) after the 115 V ac is switched off by the solid state relay. If two 115-V ac half-cycles of the same polarity are applied to the transformer, magnetic saturation occurs which causes severe waveform distortion. The polarity detector and 1-bit memory circuits store the polarity of the last half of the 60-Hz waveform applied to the transformer. The next time the shock pulse is required, the solid state relay is switched on such that the 60-Hz waveform starts with the opposite polarity.

A solid state relay offers several advantages. The switching of inductive loads by electromechanical methods generates serious transients on the power line that may adversely affect other equipment. Since solid state relays switch on at the zero voltage crossing and switch off at the zero current crossing of the 60-Hz line, inductively caused arcs are eliminated. Furthermore, it is not possible to generate the short pulse widths and the short periods discussed here with an electromechanical switching scheme.

In order to insure that the shock current remains stable for normally encountered changes in line voltage, a regulator (Sola Inc., Model 20-14-015CVN) is used between the ac line and the solid state relay. This regulator maintains an output voltage of 120 V ac to within 1/2%, with an input voltage change ±15%. The regulator is not harmonically filtered and, therefore, the 120-V ac output referred to is an rms value. Unfortunately, line voltage induced current fluctuations are frequently neglected in other designs of constant-current ac shockers.

The step-up transformer (Stancor, Model P8151, 2,400 V ac, 5 mA) develops sufficient voltage to guarantee delivery of a constant current to the animal to within 7% for resistance changes of 300% under the worst case conditions. This resistance is about 100K at .1 mA and drops to about 20K at 2.0 mA.

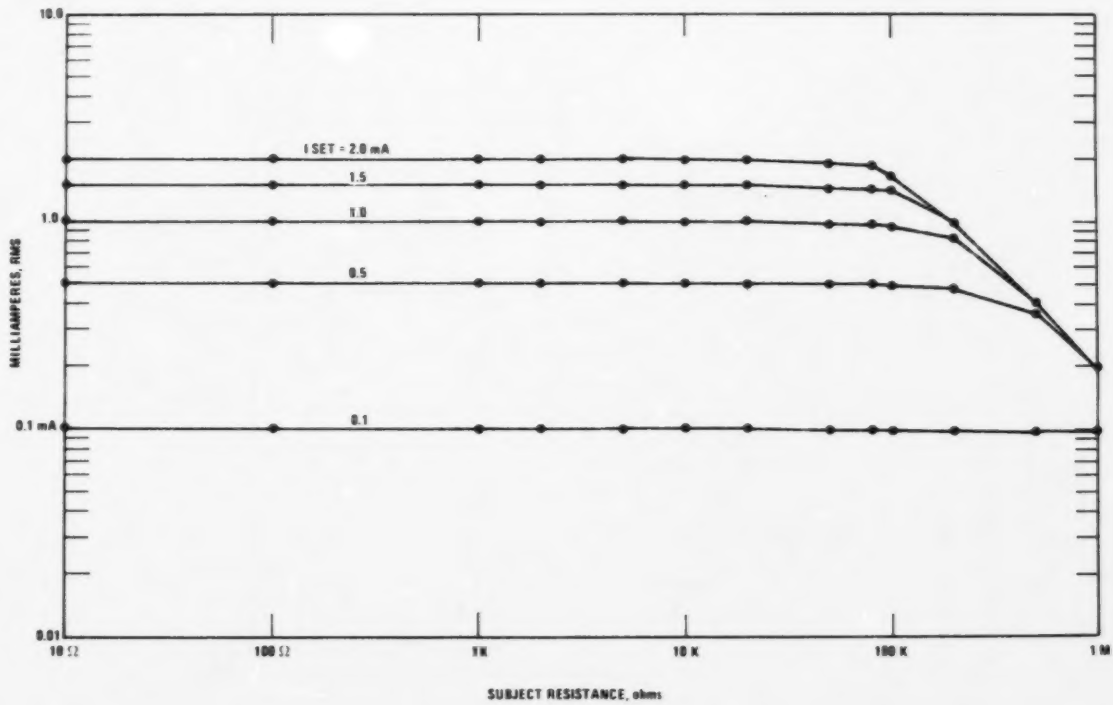

Figure 5. Load regulation as a function of simulated subject resistance for selected shock current settings.

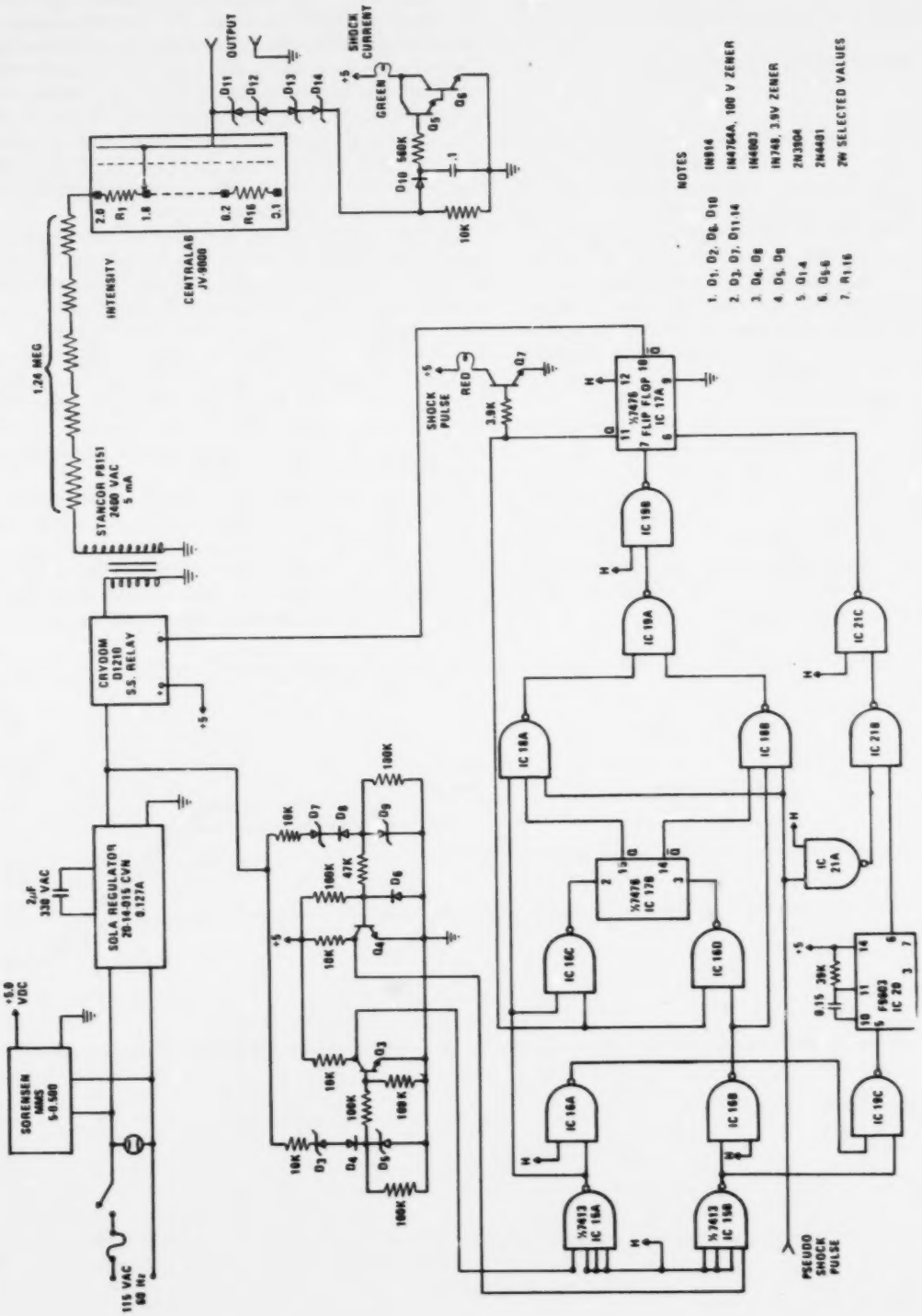

Figure 6. Schematic diagram of the output and control sections.

The worst case load regulation takes place when the ratio of source impedance to load impedance is smallest. Normally, this occurs at the highest current value. With a source impedance at about 1.3 megohm at 2.0 mA, a 300% increase in the resistance of the animal causes a 7% change in shock current. More complete load-regulation characteristics are shown in Figure 5. These data were obtained by connecting a decade resistance box to the output terminals to simulate the variation in subject resistance.

Detailed Operation of Selected Circuits

Polarity detector circuit. The polarity detector circuit is essentially two half-wave rectifier circuits including D3-D9 and Q3 and Q4. The collector of Q3 goes low when two conditions are met: (1) The output voltage of the Sola regulator is positive and (2) the output is greater than 100 V dc (see Figures 6 and 7a). The output of Q4 is identical, but triggered by -100 V. The 100-V offset is included so that the solid state relay can be switched unambiguously. The pulse generator is gated with the output of the polarity detector (as well as the 1-bit memory) to insure that the solid state relay is only switched on well before a zero voltage crossing. Since the solid state relay switches on only at zero crossings of the 115-V ac waveform, the TTL input to the relay must be enabled well before the zero crossing occurs to insure switching action at the next zero crossing.

One-bit memory and gating circuit. The function of the 1-bit memory is to store the polarity of the last half-cycle of the 115-V ac, 60-Hz waveform applied to the step-up transformer during a shock pulse. For a subsequent shock pulse, the 1-bit memory insures that the solid state relay starts conducting at the zero voltage point of the opposite polarity (see Figure 7b). The polarity at B must be opposite that at A.

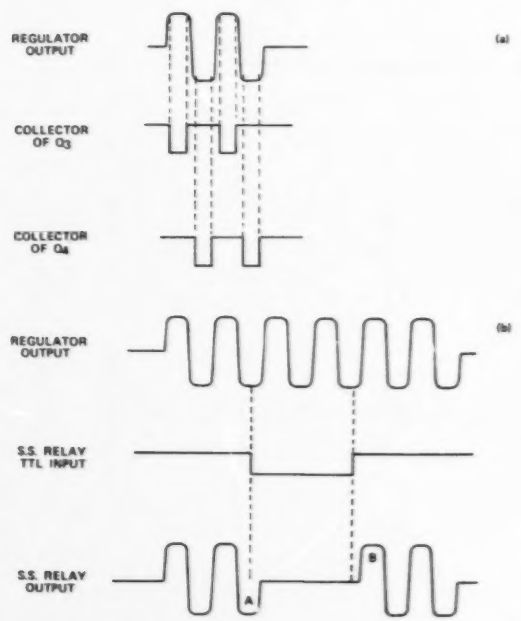

Figure 7. Operation of the polarity detection (a) and 1-bit memory and gating circuit (b).

The "Q" output of IC 17A is routed to gates IC 16C and D. Therefore, flip-flop IC 17B can only change state while the "Q" output of IC 17A is high. IC 17B therefore stores the last polarity of the 115 V ac, as indicated earlier. When the pulse generator requests the next shock pulse, the generator output is applied to gates IC 18A and IC 18B. Three conditions are necessary for an output from either of these gates: The pulse generator output must be high (i.e., a shock pulse is requested), the Q or the $\overline{Q}$ output of IC 17A must be high (which is always true), and the appropriate output must be present from the polarity detector.

PASSIVE AVOIDANCE EXPERIMENT

Method

A modification of the method of Kurtz and Pearl (1960) was used to test passive avoidance. The test chamber was divided into two compartments: a small black box (24 x 15 x 22 cm H) attached to a large white cylinder (51 cm diam x 38 cm H). The arched opening between the two compartments measured 9 cm^2 and was equipped with a removable, clear plastic guillotine door.

Twenty-one adult female Sprague-Dawley rats (approximately 300 g) were used. Animals were placed individually in the cylindrical compartment and allowed free movement between both compartments for 3 min. The times (seconds) spent in each compartment were recorded, as well as the number of times the animal crossed from one compartment to the other. At the end of the 3-min exploration period, the animal was placed in the black box with the guillotine door closed and received three footshocks, each of 3-sec duration, equally spaced over a 1-min period. Current intensities were 0, .3, .4 and .6 mA. Animals were retested for the next 6 days at 24-h intervals, and the times spent in the two compartments and number of crossovers during the 3-min exploratory period were measured. No footshock was administered during this retest period.

Results and Discussion

The utility of the constant-current ac shocker is shown in Figure 8. Animals show some initial preference for the black box, spending only 40% of their time in the cylinder during the exploratory period on the first day. This value remains fairly constant for the 0-mA controls over the 6 days of testing. Animals receiving either .3, .4 or .6 mA showed significant avoidance of the shock compartment on the day following shock administration. Since animals received no footshock following the learning procedure on Day 0, the tendency for the animals to return to the shock compartment is termed extinction. Animals receiving .3- and .4-mA footshock showed extinction on Days 3 and 6, respectively. Furthermore, the .6-mA group showed no extinction over the 6 days following footshock.

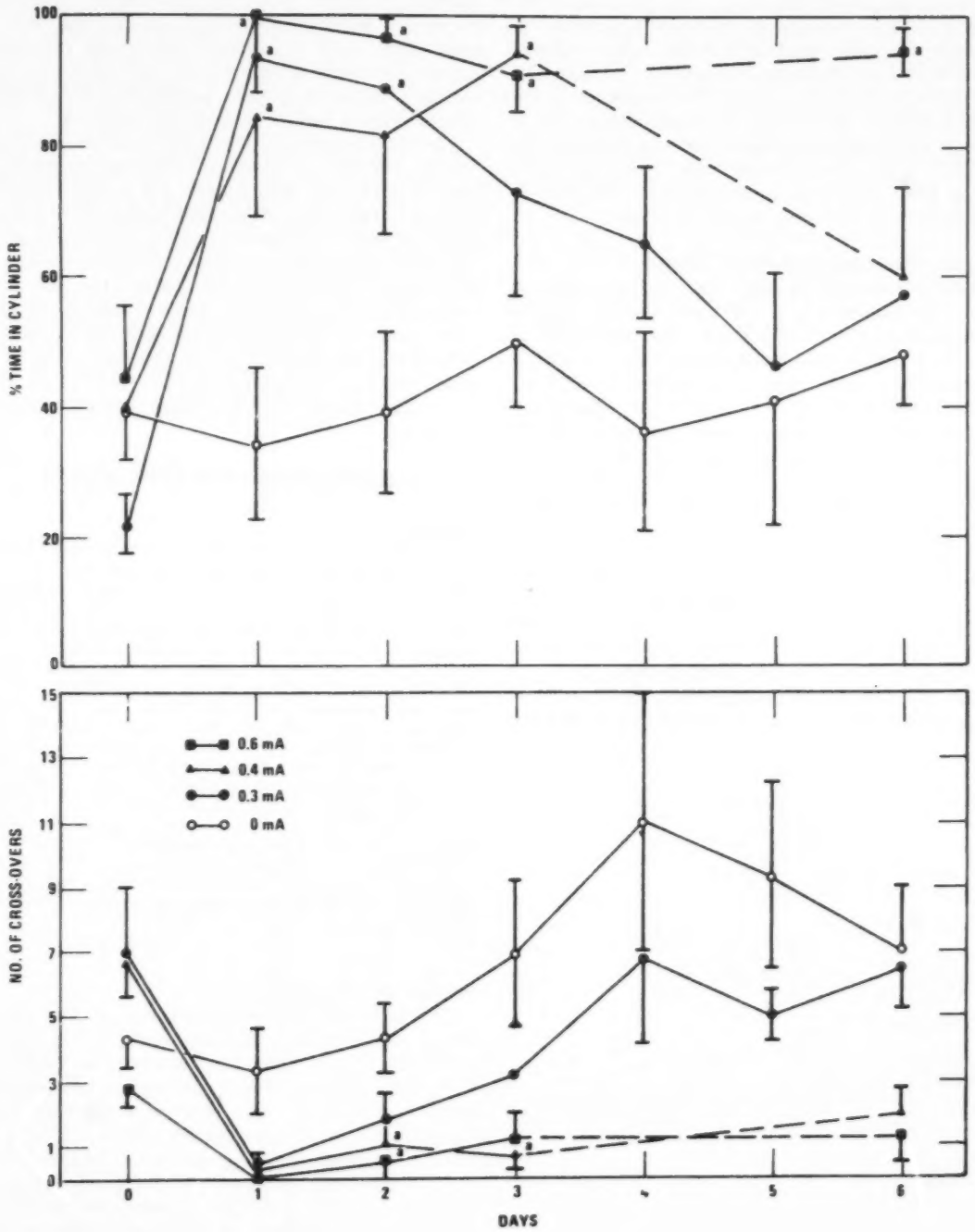

Figure 8. Effect of shock intensity on passive avoidance learning in adult female rats. Values represent percent time spent in the cylindrical compartment of the test chamber (upper figure) and mean number of crossovers between compartments (lower figure) Vertical bars represent standard error of means. [a]Values significantly different from 0-mA control (t test, $p < .05$).

Thus, the time required for extinction was related to the shock intensity. Also, Figure 8b shows that an inverse relationship exists between the number of crossovers and the rate of extinction.

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(Received for publication October 26, 1976;
revision accepted February 3, 1977.)